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Review

Research Review of a Vehicle Energy-Regenerative Suspension System

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Abstract: Vehicles are developing in the direction of energy-saving and electrification. suspension has been widely developed in the field of vehicles as a key component. Traditional hydraulic energy-supply suspensions dissipate vibration energy as waste heat to suppress vibration. This part of the energy is mainly generated by the vehicle engine. In order to effectively utilize the energy of this part, the energy-regenerative suspension with energy recovery converts the vibrational energy into electrical energy as the vehicle's energy supply equipment. This article reviews the hydraulically powered suspension of vehicles with energy recovery. The importance of such suspension in vehicle energy recovery is analyzed. The main categories of energy-regenerative suspension are illustrated from different energy recovery methods, and the research status of hydraulic energy-regenerative suspension is comprehensively analyzed. Important factors that affect the shock-absorbing and regenerative characteristics of the suspension system are studied. In addition, some unresolved challenges are also proposed, which provides a reference value for the development of energy-regenerative suspension systems for hybrid new energy vehicles

Keywords: energy loss; regenerative suspension; hydraulic regenerative suspension; regeneration energy

1. Introduction

Since the energy-saving idea was introduced in the 20th century, energy efficiency has gained attention in the automobile industry. Unlike traditional energy-regenerative suspension, which can only absorb vibration passively, the energy-regenerative suspension system with energy recovery cannot only recover vibration energy but also convert it into electrical energy, which can be stored in devices as power supply. Existing research and technical means confer the suspension system with characteristics of nonlinearity and variable stiffness to achieve smooth driving on flat pavement and absorb considerable impact energy when driving on bad pavement, thereby effectively isolating and attenuating the vibration excitation of the pavement to the car body [1]. A regenerative suspension system is introduced in the vibration exciter assembly to attenuate or eliminate the energy generated by the excitation vibration in the vertical direction. This system converts mechanical energy into electromagnetic energy through an actuator, and the electromagnetic energy is stored by energy storage elements, which can reduce vibration and recover excess energy [2–5]. The braking energy recovery system has been systematically studied by many universities and most vehicle enterprises.

After approximately 30 years of extensive research and development work and investment, the system has been successfully commercialized in hybrid and pure electric vehicles, and it greatly improves fuel economy. Considerable research has been conducted on the energy recovery potential of vehicle suspension [6]. However, the specific value of energy recovery differs. For example, simulation analysis in Reference [7] indicated that the energy recovery of the entire vehicle suspension system is only 46 W, whereas Reference [8] reported that the energy of 7500 W can be recovered in the suspension of passenger vehicles.

In view of the main factors affecting the recovery efficiency of energy-regenerative suspension. Wei and Taghavifar [9] studied the influences of different factors, such as speed, frequency, pavement roughness, and harmonic amplitude, on instantaneous power under random and harmonic excitation of pavement. When driving at 20 km/h, the road input amplitude is 0.01 m, 2 Hz, and the maximum instantaneous power is 79 W. The instantaneous power levels of the front suspension and rear suspension are approximately 63 and 43 W, respectively. We used frequency and time domains to predict the average dissipated power of suspension dampers with different frequencies; results indicated that instantaneous power is proportional to instantaneous velocity, and the average power is proportional to the average velocity. The maximum average power is 3900 W when the frequency is 12 Hz. When the speed increases from 10 km/h to 13 km/h, the average power also increases. When the speed increases from 13 km/h to 20 km/h, the average power decreases from 57.8 W to 51.6 W. When the input frequency is 2 Hz and the amplitudes are 0.01 and 0.05 m, the minimum average power obtained is 51.4 W, and the maximum average power is 1289 W. As the road amplitude increases, the dissipated power increases. Zhang et al. [10] stated that vehicle speed is a key parameter in the pavement roughness model, and the regenerative power is proportional to the driving speed. At the same speed of 80 km/h, the same off-road vehicles can regenerate 128 W (B-Class), 512 W (C-Class), and 2048 W (D-class). With a speed of 60 km/h on the C-Class pavement, each damper of small cars, off-road vehicles, and bus quarter suspension models can harvest energy up to 105 W, 384 W, and 1152 W, respectively. To sum up, new energy-power-supplied cars experience imperfection of the existing power supply technology; have limited power supply, especially in a low-temperature environment; and easily cause the power supply system to work abnormally. The energy-regenerative suspension system stores the energy in the vibration process as energy supply, which can effectively reduce the body vibration and improve the power supply efficiency of vehicles. Therefore, the recovery energy efficiency and recovery method of the energy-regenerative suspension of hybrid electric new energy vehicles and the factors that affect the vibration reduction and energy-regenerative characteristics of the suspension system were studied.

Most of the research is based on the influence of road irregularity and driving speed on the energy recovery efficiency of passenger cars, while the impact on vehicle parameters has only been proposed in a few studies. Therefore, in addition to the analysis of the hydraulic energy-regenerative suspension system, the impact of vehicle adjustment parameters on the recovery efficiency of the energy-regenerative suspension was further analyzed.

The main contributions of this work concentrate on three aspects,

1. The overall design scheme of the energy-regenerative suspension system is designed, and the model of the energy-efficiency of the hydraulic energy-regenerative suspension is established.
2. The influence factors of vehicle adjustment parameters on the recovery efficiency of the hydraulic energy-regenerative suspension were qualitatively analyzed, and the dynamic characteristics of the double-tube shock absorber were simulated and analyzed.
3. Aiming at the differences in the efficiency of current hydraulic energy-regenerative suspension key challenges are raised.

The rest of this article is organized as follows: Section 2 presents the overall design of the energy-fed suspension system. Section 3 analyzes the current state of vehicle energy loss. Section 4 explains the principles of electromagnetic and hydraulic suspension systems with energy recovery. The applications of electromagnetic and hydraulic energy-regenerative suspension systems in vehicles are listed. Section 5 lists the current research status of hydraulic energy-regenerative suspension, analyzes the important factors affecting the vibration damping characteristics and energy-regenerative characteristics of suspension systems, and proposes some existing challenges for energy-feeding suspensions.

2. General Design Scheme of the Energy-Regenerative Suspension System

The shock absorber removes the energy dissipated in the suspension from the vibration caused by rough pavement. The shock absorber needs three parts, namely, suspension vibration input, transmission, and generator modules. The suspension vibration input module transfers kinetic energy to the transmission module, which makes the shaft move in both directions. The transmission module is composed of helical gear and one-way clutch, which converts the motor's two-way shaft movement into one-way movement. The generator module generates electricity to power the low-power electrical devices of electric vehicles. The total damping force of the energy-regenerative damper is divided into equivalent controllable and passive damping forces. The equivalent controllable damping force is the rotary resistance of the hydraulic motor caused by the back-emf of the generator, which is used to realize the semiactive control of the suspension system. The passive damping force is the uncontrollable damping force caused by the rotation resistance of no-load rotation and the passive damping of orifice and oil pipelines in the actuator. A DC brushless generator is used, and the obtained three-phase AC power is converted into DC by full-wave rectification to charge the battery. The overall scheme of the vehicle's energy regenerative suspension system is shown in Figure 1.

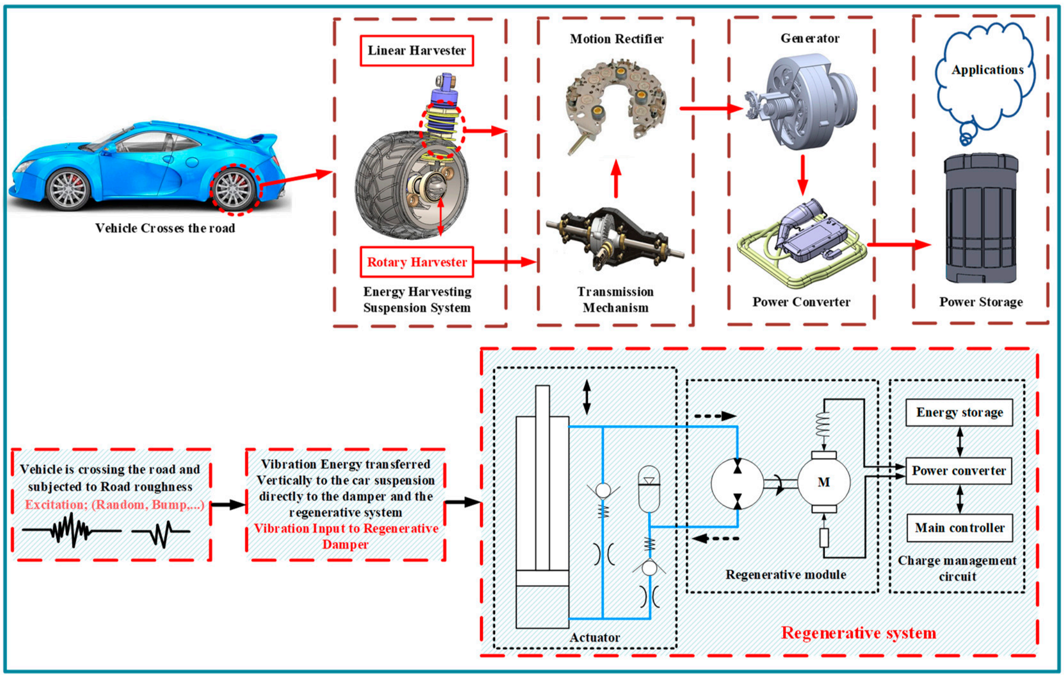

Figure 1. The overall scheme of the vehicle's energy regenerative suspension system. (Reprinted (adapted) with permission from Ref. [11] Copyright (2018) Elsevier).

3. Research Status of Energy Loss

A report released by the US Environmental Protection Association in conjunction with universities and companies, such as MIT and Ford, in 2008 showed that only approximately one-fifth of the fuel energy of conventional passenger cars is converted into mechanical energy, and less than half of that mechanical energy is transferred to driving wheels for use in vehicles [12]. In the 2011 report issued by the US Energy Administration, the 2005 2.5 L Camry's vehicle energy flow was given, in which only 16% of the fuel was used to drive the vehicle, which was utilized to overcome the friction from the pavement and air resistance [13]. Most of the energy loss was concentrated on the engine, approximately 75% (such as heat, pump, and friction losses), but the tire loss is approximately 23% [14], vehicle energy consumption is shown in Figure 2. Carruthers [15] predicted the energy consumption of a vehicle's damper for different road conditions and vehicle speeds and that the average dissipated powers of the vehicle under urban and highway driving speeds are 80 W and 140 W, respectively. Depending on the period of drive, only 12–30% of the fuel in a traditional car is used for driving, and the rest of the energy is lost to the engine and transmission system or to the power accessories. Analysis of a vehicle's energy flow can be found in three ways to improve fuel economy, namely, engine heat, brake energy, and suspension energy recoveries. The research status of the energy recovery system for vehicle engine waste heat is shown in an article published by Bell in Science [16]. Briggs [17] studied the displacement recovery of a diesel-electric hybrid electric bus and proposed that turbogenerators are significant in reducing fuel consumption. Zhang [18] developed an efficient electromagnetic energy-harvesting system for recovering vibrational energy, which can recover up to 55.5%. The average efficiency of the shock absorber designed by Salman [19] is 40%, and the maximum efficiency is 52%. Pham [20] developed an active suspension system with energy recovery. Compared with the passive suspension system, the RMS value for vehicle body acceleration is reduced by more than 31%, and energy consumption is reduced by approximately 2.8%. Shi [21] introduced a suspension model in a hybrid vehicle. On the D-class road, the fuel consumption per 100 km is reduced by approximately 0.4 L; on the B-class road, the fuel consumption per 100 km is reduced by approximately 0.07 L; on the C-class road, the fuel consumption per 100 km is reduced by approximately 0.2 L.

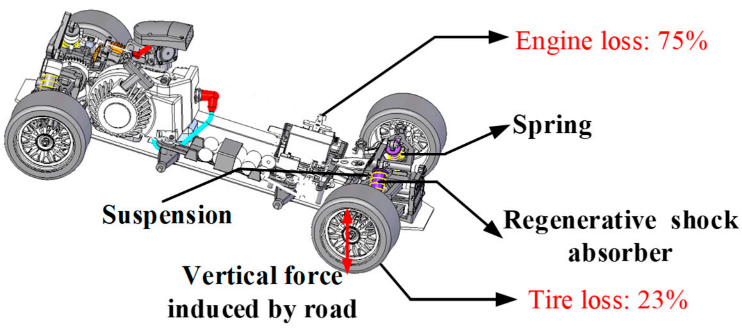

Figure 2. Vehicle energy consumption.

4. Research Status of the Energy-Regenerative Suspension System

Shock absorbers are an important part of a vehicle suspension system. When driving on uneven roads, the shock absorbers play the role of supporting the body and vibration buffer to ensure safe and comfortable driving. In addition to the vehicle movement, most of the vehicle energy is dissipated by vibration, heat, and friction. A suspension system with an energy recovery function has been studied to reduce energy waste. The optimized design of regenerative shock absorbers has been deeply studied. Regenerative shock absorbers are mainly divided into hydraulic and electromagnetic according to different working principles.

Hydraulic regenerative actuators include an energy recovery device for collecting the energy generated by shock absorbers. They can be single- or double-tube damping with an electronic control valve [22]. Traditional hydraulic shock absorbers convert vibrational energy into heat and then dissipate heat into the environment. With the discovery of the benefits of energy recovery and reuse, the hydraulic regenerative suspension has been extensively developed, and the mechanical energy of the hydraulic suspension vibration is recovered and stored in the form of hydraulic energy, the hydraulic regenerative suspension is shown in Figure 3. The working principle of the electromagnetic energy-regenerative suspension is to replace traditional shock absorbers with electromagnetic actuators when vehicles start to vibrate due to uneven pavement. The motor coil cuts the magnetic induction line and outputs the voltage to the outside. The energy generated by the mechanical vibration is converted into electrical energy and stored in energy storage devices, the electromagnetic energy regenerative suspension is shown in Figure 4.

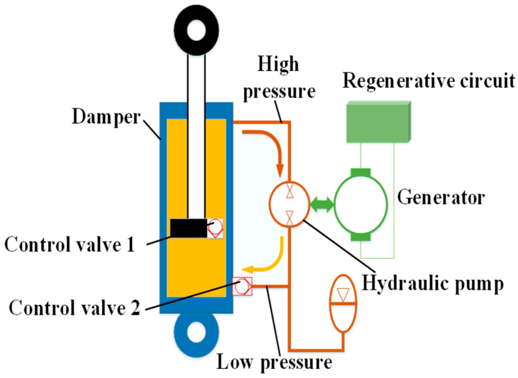

Figure 3. Hydraulic regenerative suspension.

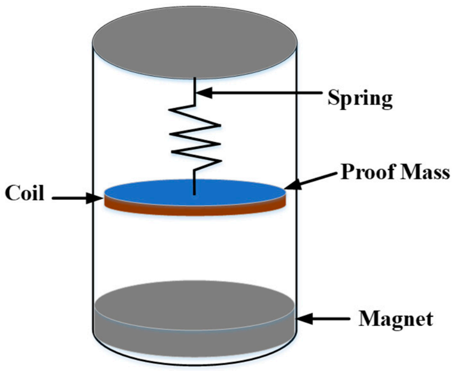

Figure 4. An electromagnetic energy regenerative suspension (Reproduced and drawn with permission from Ref. [10]).

In 1996, Suda and Shiiba proposed a DC-generator-based energy recovery method. Graves et al. [23] designed an energy-regenerative damper using a rotating DC motor and a ballot screw mechanism. The efficiency of the device is higher than that of the DC generator, and the price is lower. Goldner and Zerigian [8] used an optimized design of regenerative electromagnetic dampers to verify the effectiveness of converting the energy generated by the vertical vibration of vehicles into electrical energy. A traditional shock absorber can achieve a peak power of 68 W when the vehicle is driving at a smooth campus road at 30 km/h. Martins [6] compared the layout of hydraulic and electromagnetic active suspensions and demonstrated the capability of linear permanent magnet brakes in vehicle suspension systems. Li [24] developed a direct-drive brushless tube permanent-magnet actuator that is connected in parallel with a passive spring and a damper to transmit power and convert the energy generated by vibration into power; using a linear or rotary electromagnetic generator converts the vibration capability of the system into electrical energy. Li et al. [25] designed a regenerative shock absorber with a rack and pinion mechanism. A regenerative damper based on power electronic charging control has real-time control of the damping characteristics of the suspension system by using a power electronic controller to process the generated electricity and convert it into electrical energy. The concept of regenerative damping is similar to regenerative braking to some extent, but it is to recover the mechanical vibration energy into the battery [26–28]. Their equipment can produce a peak power of 68 W and an average power of 19 W. In consideration of the efficiency of the engine and generator, 300 W of power at this time means approximately 1800 W of fuel consumption. For commercial and off-road vehicles with great weight and severe driving conditions, the energy recovery potential is high. Liu [29] proposed a new type of electromagnetic active suspension with an energy regeneration structure.

Experiments on roads above B-Class can recover 18% of vibration energy and provide more than 11% of power for control requirements. Roshan [30] verified the effectiveness of an energy recovery damper based on a power electronic controller. The experimental results showed that the control system can provide constant regenerative damping for various mechanical vibration amplitudes. Zuo [31] designed a power recovery shock absorber with high power density and modification capacity to improve energy recovery efficiency consumed by vehicle suspension vibration and reduce the impact force caused by vibration. Lei Zuo introduced the "mechanical movement rectifier," which converts the oscillatory vibration of the suspension into one-way rotation of the generator, and applied it to a harvester. In the case of high frequency, the recovery efficiency is 60%. Zhang [32] proposed a regenerative shock absorber with a two-speed mechanism. Compared with a traditional regenerative shock absorber, the regenerative damper increased its speed by twice but could not achieve motion conversion. When the regenerative shock absorber system was subjected to a large motion load, it was prone to failure. To achieve motion conversion, Zhang [33] proposed a new indirect-drive regenerative damper system that uses the arm gear mechanism to achieve linear transformation of rotational motion and increase energy-harvesting output by increasing its input speed. Gao [34] studied the energy flow mechanism inside an active suspension system and the vibration energy caused by rough pavement. An electromagnetic active suspension control strategy was designed on the basis of the energy flow mechanism of the system to reduce the system energy consumption by 14.51%. The main power can recover 2.45% of the extra energy. Tucker et al. drove the hydraulic power generation module to generate electricity in accordance with the one-way fluidity of oil. The designed energy regenerative suspension can keep the rotation of the motor in one direction all the time, which not only improves the energy recovery characteristics but also has a high reliability [35]. Zhang [36] designed a hydraulic energy recovery shock absorber and analyzed its suspension performance. Wang [37] determined that under the sinusoidal excitation of 1 Hz and 25 mm, the recoverable power is 26 W, and the efficiency is 40%. Under the vibration input with 7.5 mm and 2.5 Hz, the average power of 4.3 W can be obtained through a shock absorber [38]. The energy recovery efficiency of the energy-regenerative suspension system is 75%. The preceding analysis implied that the energy-regenerative shock absorber of a passenger car driving on the general pavement (C-Class) at 60 miles/h can recover 300 W of electric energy, whereas the power of a typical generator of a passenger car is 500–600 W; the efficiency is approximately 55% [39]. Zhang [40] designed an efficient energy recovery shock absorber with an average efficiency of 44.24% and a maximum efficiency of 54.98% by using an ultracapacitor. A shock absorber using a mechanical motion rectifier was proposed, which can convert random vibration into regular one-way rotation. The efficiency of the sample shock absorber designed by them can reach more than 60% at high vibration frequency and generate more than 15 W electric energy when the driving speed is 24.14 km/h.

5. Research Status of Hydraulic Energy-Regenerative Suspension

The core component of the energy-regenerative suspension system is energy-regenerative shock absorber. With the wide application of piezoelectric crystals and intelligent materials, energy-regenerative shock absorbers are mainly divided into hydraulic and electromagnetic [41]. In the current research on the energy-regenerative suspension, the hydraulic energy-regenerative suspension has a relatively simple structure compared with the electromagnetic energy-regenerative suspension. Therefore, the hydraulic energy-regenerative suspension is put into the application earlier. The so-called hydraulic energy-regenerative suspension is to add a hydraulic device on the basis of the traditional shock absorber. During the mechanical vibration in the vertical direction of the suspension, the hydraulic energy is generated by the telescopic movement of the piston, which is transmitted to the hydraulic accumulator through relevant pipelines and electronic equipment [42]. In foreign countries, Glenn R et al. applied the hydraulic energy-regenerative suspension to vehicle suspension to improve the trafficability and comfort of vehicles on complex roads and performed a simulation analysis on the vibration damping performance and energy recovery characteristics of the suspension [43,44].

Kowal et al. applied a multifrequency excitation to the energy-regenerative suspension to verify the vibration damping and energy recovery characteristics of the hydraulically regenerative suspension. A force generator was added to the regenerative suspension to form a hydraulic regenerative active suspension system for improving its vibration-damping characteristics [45]. Audi Motors conducted a suspension regenerative potential test on passenger cars on different roads [46]. Results showed that the average recovery power of the suspension on roads in Germany was 150 W, that on a newly paved asphalt highway was 3 W, and that on a rugged township road was as high as 613 W. In this test, CO_2 emissions per kilometer were reduced by 3 g. Chen Shian proposed a new type of hydraulic energy-regenerative suspension, elucidated the working principle of the system, and studied its working characteristics through simulation analysis [47,48]. Liu [49] proposed an energy recovery shock absorber based on a mechanical motion rectifier, which used a ballscrew and two one-way clutches to replace the traditional oil damper to generate higher energy recovery capacity. Fang et al. optimized the design of the hydraulic energy-regenerative suspension and adjusted the damping coefficient of the energy-regenerative suspension by controlling the load current [50]. Li and Peter [51] designed a hydraulic damper for energy recovery. In their study, they elaborated on how the hydraulic damper used a hydraulic generator to recover mechanical energy from its oil flow. Fang [52] designed a hydraulic electromagnetic energy-regenerative shock absorber, which can recover approximately 200 W energy under the excitation of 10 Hz and 3 mm; the energy recovery efficiency is only 16.6%. The rectification efficiency of the hydraulic rectifier decreases as the excitation frequency increases, which finally leads to a decrease in energy recovery efficiency. Guo et al. [53] invented a pump-type regenerative cross-linked suspension system that achieves different oil flow patterns by changing the cross-linking form. Asadi [54] proposed an electromagnetic hybrid damper with energy recovery. Levant Power of the United States has conducted numerous simulations and tests on the effect of its hydroelectric energy-regenerative shock absorber on fuel economy in different models [55]. The application of this technology to military and off-road vehicles can improve fuel economy by more than 6%, reaching 7% to 10% in hybrid and pure electric vehicles. Another analysis of the company's data showed that heavy trucks fitted with six energy-regenerative shock absorbers can produce 1 kW average recovery power on normal roads, which is sufficient to replace the high-power vehicle regenerators used in heavy trucks and military vehicles. Lei and Zhang [56] of the State University of New York used the comprehensive mathematical model of the "vehicle–road–suspension energy recovery system" to evaluate the energy recovery potential of the vehicle suspension system. As shown in Figure 5, this model used ISO2631-1:1997 to establish the excitation model of uneven pavement and the displacement power spectral densities of different pavements, and the H2 norm was used to obtain the average energy dissipation of the traditional shock absorber. Results showed that the maximum recoverable energies of four shock absorbers of a 1.5 t passenger car are 100 W, 400 W, and 1600 W when driving at 60 mile/h on B-, C-, and D-class roads. This estimation method does not consider the energy-regenerative efficiency of the energy recovery system, nor does it distinguish the structural form of the energy-regenerative suspension system, which is only the ideal energy that can be recovered. The vibration effect due to the dynamic coupling between the suspension spring and the vehicle mass is relieved by the damper. Traditional dampers convert mechanical energy into heat energy with a fixed damping coefficient. The power dissipation of a traditional damper is estimated to be between 100 W and 400 W when a typical medium bus is driving on a good road at 100 km/h.

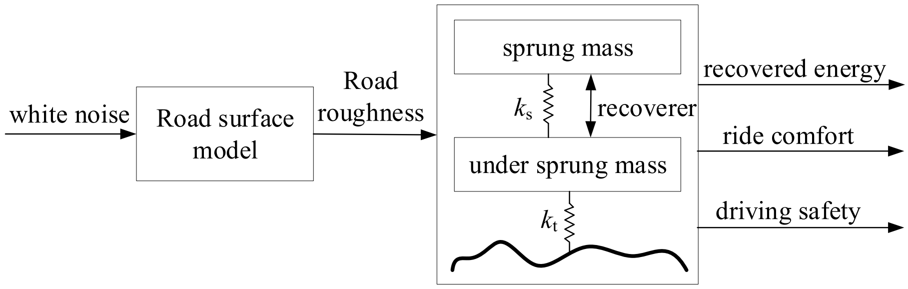

Figure 5. Vehicle–pavement-suspension energy recovery system model.

The important evaluation index of energy-regenerative suspension is hydraulic energy-regenerative suspension efficiency. As shown in Figure 3, the hydraulic energy feeder is composed of hydraulic motor, generator, shaft coupling, and other components. In order to better analyze the efficiency of hydraulic suspension, a model of efficiency was established [57].

The total equivalent damping force $F_{semi\text{-}active}$ of the hydraulic energy-regenerative shock absorber can be expressed as,

$$\begin{aligned} F_{semi-active} &= A_c P_{up,controllable} - A P_{down,controllable} \\ &= \begin{cases} \frac{\pi^3 k_t k_e \eta_v \left(D^2 - d_{rod}^2\right)^2 v(t)}{q^2 \eta_m (R_{in} + R_{ex})}, & v(t) \geq 0 \\ -\frac{\pi^3 k_t k_e \eta_v d_{rod}^4 v(t)}{q^2 \eta_m (R_{in} + R_{ex})}, & v(t) \leq 0 \end{cases} \end{aligned} \tag{1}$$

where A_c is the cross-sectional area of the annular cavity between the cylinder and the piston rod, $P_{up,controllable}$ is hydraulic pressure in the upper cavity of the actuator, $P_{down,controllable}$ is hydraulic pressure in the lower cavity of the actuator, k_t is generator torque constant. k_e is the back-EMF constant of generator, η_v is the volumetric efficiency of hydraulic motors, η_m is the mechanical efficiency of hydraulic motors. q is displacement of hydraulic motor. R_{in} is generator internal resistance, R_{ex} is the external load of the generator, $v(t)$ is the speed of the piston in a working cylinder, D is working cylinder diameter, and d_{road} is piston rod diameter.

The output current I of the generator can be expressed as,

$$I = \frac{2\pi k_e \eta_v}{q(R_{in} + R_{ex})} Q_{pump} = \begin{cases} \frac{\pi^2 k_e \eta_v \left(D^2 - d_{rod}^2\right)}{2q(R_{in} + R_{ex})} v(t), v(t) \geq 0 \\ \frac{\pi^2 k_e \eta_v d_{rod}^2}{2q(R_{in} + R_{ex})} \left|v(t)\right|, \quad v(t) \leq 0 \end{cases}. \tag{2}$$

The recoverable energy-regenerative suspension efficiency $P_{regenerator}$ of the energy regenerative suspension system can be expressed as,

$$P_{regenerative} = I^2 R_{ex} = \begin{cases} \frac{\pi^4 k_e^2 \eta_v^2 \left(D^2 - d_{rod}^2\right)^2 R_{ex}}{4q^2 (R_{in} + R_{ex})^2} v^2(t), & v(t) \geq 0 \\ \frac{\pi^4 k_e^2 \eta_v^2 d_{rod}^4 R_{ex}}{4q^2 (R_{in} + R_{ex})^2} v^2(t), & v(t) \leq 0 \end{cases}. \tag{3}$$

Regarding the energy recovery capability of vehicle energy-regenerative suspension, some researchers have conducted experimental and theoretical research on the energy recovery of vehicle energy-regenerative suspension. However, their recovery capabilities are quite different, Table 1 lists some researchers' investigations on the energy recovery of vehicle energy-regenerative suspension systems. Among them, *A* represents "very good", *B* represents "good", *C* represents "average", *D* represents "poor", and *E* represents "very poor".

Table 1. Survey of the conducted simulation-based investigations in terms of energy-regenerative-based shock absorbers.

No.	References	Road Conditioning	Model Type	Velocity	Regenerated Power
13	[58]	A-class B-class C-class D-class E-class	minibus	30 km/h 30 km/h 30 km/h 30 km/h 30 km/h	2.08 W 8.33 W 33.34 W 133.37 W 533.21 W
6	[59]	B-class C-class D-class	7-Degrees of freedom full vehicle	10 m/h 20 m/h 30 m/h 10 m/h 20 m/h 30 m/h 10 m/h 20 m/h 30 m/h	42.38 W 89.53 W 156.05 W 193.14 W 371.56 W 684.32 W 850.64 W 1712.70 W 2999.30 W
1	[60]	C-class	Car off-road vehicle Passenger car	60 km/h	105.2 W 384 W 1152 W
2	[56]	B-class C-class D-class	Passenger car	—	100 W 400 W 1600 W
3	[46]	Ordinary road Newasphalt road ruggedness township road		—	150 W 3 W 613 W
4	[38]	C-class	Passenger car	60 mile/h	300 W
5	[40]	—	—	24.14 km/h	15 W
7	[61]	B-class C-class D-class	— — —	— — —	≈25 W ≈100 W ≈410 W
8	[21]	A-class B-class C-class D-class	Hybrid electric vehicle	— — — —	≈10 W ≈50 W ≈220 W ≈790 W
9	[62]	A-class B-class C-class D-class	A quarter car model	20 m/s	4.9 W 17.7 W 49.2 W 45 W
10	[63]	C-class	Passenger car	50 km/h	50–60 W
11	[64]	C-class	Passenger car truck	30 m/s 30 m/s	108 W 864 W
12	[65]	C-class	Passenger car	120 km/h	500–1000 W
14	[66]	A-class B-class C-class D-class	A quarter car model	10 m/s 10 m/s 10 m/s 10 m/s	127.6 W 138.8 W 172.8 W 379.8 W
15	[67]	B-class C-class D-class	vehicle	60 km/h 80 km/h 20 km/h 80 km/h 20 km/h 40 km/h	4 W 10 W 7 W 15 W 13 W 25 W

The output damping force of the energy-regenerative suspension system is an important factor that affects the vibration damping and energy-regenerative characteristics of the suspension system. On the basis of the matching scheme of suspension parameters in different excitation frequency bands, accurate output damping force is the premise to ensure the suspension system characteristic in the optimal state. Lei [56] studied the effects of road roughness, vehicle speed, suspension stiffness, shock absorber damping, tire stiffness, wheel, and wheel mass on vehicle performance and energy recovery. The simulation results showed that road roughness, tire stiffness, and vehicle driving speed have great influences on energy recovery, whereas the suspension stiffness and shock absorber damping have small influences. Tire stiffness affects the power of vehicle suspension, and suspension stiffness and damping influence vehicle comfort and safety. They conducted road tests and found that the suspension of a typical medium-sized passenger car driving at an average speed of 60 mile/h on B- and C-Class roads can recover an average power of 100–400 W. The super compact vehicle is expected to recover energy 60 W and drive at 25 mile/h on a campus road. Zhang and Guo of Wuhan University of Technology [58] discussed the energy-regenerative potential of vehicles through the combination of simulation calculation and real-world road test. The main factors that affect the regenerative power were analyzed in depth. Tire stiffness, pavement grade, and vehicle speed are the key factors that affect energy feed power. Experiments showed that for passenger cars, regenerative power is low when driving on roads above B-Class. When driving on roads below C-Class or applying the energy-suspension system to heavy-duty and off-road vehicles, the regenerative power has a better value. Zhang [10] conducted a test on the characteristics of oil temperature and damping force. The test showed that the damping oil temperature increases with the increase in excitation time, and the damping force decreases with the increase in oil temperature. The equilibrium temperature is almost 105 °C at a maximum speed of 0.52 m/s sinusoidal excitation. When the temperature is from 20 °C to 100 °C, the damping force is significantly reduced. The increase in damping oil temperature is one of the influencing factors of suspension energy recovery. Zou [68] proposed a hydraulic interconnected suspension based on energy-regenerative shock absorbers. The damping characteristics and energy recovery capacity of the system were comprehensively analyzed on the basis of a 7-DOF full-suspension model; the energy recovery efficiency can reach 49.87%. Zhang [60] designed an electro-hydraulic energy-harvesting damper suitable for off-road vehicles. From the experiment, the range of damping force and the amount of recovered power depend on the excitation density and external load value. The external load value is 10 Ω, the maximum excitation speed is 0.52 m/s, the output peak power is approximately 200 W, and the average power is 110.6 W. Guan [61] studied the dynamic characteristics of a double-tube shock absorber. Experimental data implied that under the same excitation amplitude, a high excitation frequency leads to high damping force. The damping force can be increased by increasing the vibration amplitude at a fixed angular velocity or by accelerating the excitation frequency at the same vibration amplitude. They also analyzed the relationship between the dynamic damping coefficient and the excitation frequency and speed, the effects of frequency on the maximum damping force is shown in Figure 6.

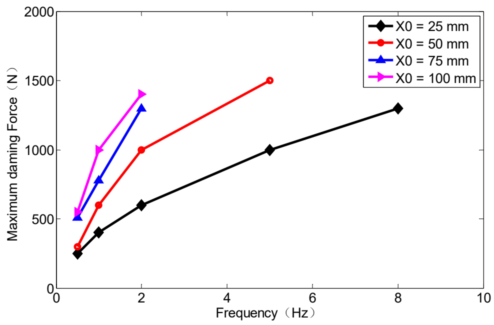

Figure 6. Effects of frequency on the maximum damping force. (Reprinted (adapted) with permission from Ref. [61] Copyright (2019) Elsevier]).

6. Conclusions

The energy recovery efficiency, recovery method, and factors that affect the regenerative and damping characteristics of the energy-regenerative suspension system are studied. Energy efficiency can be recovered by the energy-regenerative suspension system at approximately 50%. For example, cars, off-road vehicles, and passenger cars can recover 105.2 W, 384 W, and 1152 W of energy at a speed of 60 km/h on a C-Class pavement [10]. The suspension model is introduced in hybrid cars. On D-Class roads, the fuel consumption per 100 km is reduced by approximately 0.4 L; on B-Class roads, the fuel consumption per 100 km is reduced by approximately 0.07 L; on C-Class roads, the fuel consumption per 100 km is reduced by approximately 0.2 L [21]. The damping and energy-regenerative characteristics of the output of the hydraulic energy-regenerative suspension system are mainly affected by damping force, road roughness, vehicle speed, suspension stiffness, tire stiffness, wheel, and wheel mass. According to a road test conducted by Lei Zuo, the suspension of a typical medium-sized passenger car driving at an average speed of 60 mile/h on B- and C-Class roads can recover an average power of 100–400 W. The suspension is expected to recover energy of 60 W in a super-compact vehicle driving at 25 mile/h [56]. Zhang designed an electro-hydraulic energy recovery damper. The external load value is 10 Ω, the maximum excitation speed is 0.52 m/s, the output peak power is approximately 200 W, and the average power is 110.6 W [60].

The introduction of the energy-regenerative system in the traditional suspension can improve the energy utilization rate of vehicles on the one hand and be beneficial to energy regeneration on the other hand to improve the comprehensive performance of vehicles. Combined with the research on the existing hydraulic energy-regenerative suspension of vehicles, in addition to the loss of hydraulic energy-regenerative in the process of energy consumption, there is also a part of the loss in the process of turning mechanical energy to electric. How to reduce the overall energy consumption will be an important problem. In addition, the matching problem of the hydraulic energy-supply suspension system and the vehicle power system should also be considered. When the hydraulic energy-regenerative system is applied to the vehicle, although the vehicle has a large capacity of energy storage equipment, it still needs to solve the problem of matching charging equipment and charging equipment.

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